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Optimization Technology for Fault-Resistance Structure of Longitudinal Deformation Joints in Tunnels in Strong Earthquake Zones

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Abstract: To address the challenges of faulting, leakage, and other damages in longitudinal deformation joints of tunnels in strong earthquake zones, which can lead to structural failure under seismic action, this paper systematically analyzes the failure mechanisms and existing technical shortcomings of fault-resistance structures in longitudinal deformation joints based on the seismic response characteristics of tunnels in such zones. By reviewing damage cases of tunnel deformation joints in the Wenchuan and Jiuzhaigou earthquakes, three typical failure modes are identified: "tearing of rubber waterstops, crushing of filling materials between joints, and detachment of anchoring structures." The core cause lies in the inadequate adaptation of structural design to the load characteristics of "large displacement and high stress" in strong earthquake zones. In response, a three-dimensional optimization technology system encompassing "materials-structure-construction" is proposed: At the material level, a composite waterstop material with high elasticity and aging resistance is developed; at the structural level, an innovative combined structure of "mortise-tenon type limit + multiple waterstops" is introduced; and at the construction level, a quality control process of "precise positioning-layered pouring-dynamic monitoring" is established. Numerical simulations and model tests demonstrate that the optimized structure can withstand ± 150mm longitudinal dislocation and ± 80mm transverse displacement, reducing leakage by over 90% and enhancing fault-resistance by 2.3 times compared to traditional structures, providing crucial technical support for the seismic safety of tunnel engineering in strong earthquake zones.

Keywords: Tunnels in strong earthquake zones; Longitudinal deformation joints; Fault-resistance structure; Waterstop materials; Mortise-tenon type limit

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1. Introduction

Tunnels in strong earthquake zones (areas with a peak ground acceleration of ≥ 0.2g) serve as vital transportation lifelines, and their structural safety directly determines the accessibility of rescue routes after earthquakes. As a weak part of tunnel structures, longitudinal deformation joints are primarily used to release temperature stress and uneven settlement. However, under strong earthquakes, the longitudinal and transverse displacements of tunnels caused by fault dislocation can easily lead to structural damage to deformation joints. During the Wenchuan earthquake, the maximum dislocation of the longitudinal deformation joint in the Zipingpu Tunnel reached 180 mm, with the rubber waterstop completely torn, resulting in large-scale leakage. During the Jiuzhaigou earthquake, the filling material of the deformation joint in the Pingwu Tunnel was crushed, the anchor bolts were fractured, and through cracks appeared in the structure.

Currently, most longitudinal deformation joints adopt the traditional structure of "medium-buried waterstop + back-adhesive waterstop + caulking material," which can only accommodate small displacements of ± 50 mm and cannot meet the requirements for large displacements in strong earthquake zones. With the accelerated construction of transportation networks in strong earthquake zones in western China, there is an urgent need to develop optimized fault-resistant structures that are compatible with the characteristics of strong earthquake loads. This holds significant engineering value in enhancing the seismic resilience of tunnel projects and ensuring the smooth passage of lifelines after earthquakes.

2. Failure mechanism and damage characteristics of longitudinal deformation joints in tunnels in strong earthquake zones

2.1. Mechanical characteristics of tunnel deformation joints under seismic loads

Longitudinal deformation joints in tunnels in strong earthquake zones are subjected to "three-dimensional composite loads": longitudinally, tensile or compressive displacements occur due to fault dislocation, easily leading to tensile failure of the waterproof structure at the deformation joints; horizontally, shear deformation is induced by the propagation of seismic waves, exacerbating the relative dislocation of structures on both sides of the joint; vertically, differential settlement due to uneven ground subsidence further amplifies the local stress concentration effect. Through FLAC3D numerical simulation analysis, the stress concentration coefficient at deformation joints under strong earthquakes reaches 2.5–3.0, significantly exceeding that of tunnels in ordinary areas (1.2–1.5).

Moreover, the displacement response exhibits characteristics of "instantaneous mutation and extremely large amplitude." Under a ground motion of 0.4 g, the longitudinal displacement of deformation joints can reach 120–180 mm, and the transverse displacement can reach 60–100 mm, which is 3–5 times that of ordinary areas. These simulation results are highly consistent with the data from previous 1:5 tunnel model experiments, confirming the extreme mechanical environment faced by tunnel deformation joints in strong earthquake zones. They also highlight the critical role of optimized structures in accommodating large displacements and resisting stress concentration, providing both numerical and experimental support for the subsequent waterproofing and structural design of deformation joints.

2.2. Analysis of typical failure modes and causes

2.2.1. Tearing failure of rubber waterstops

Traditional buried rubber waterstops are made of natural rubber with a tensile strength of only 15 MPa. Under strong seismic activity and large displacements, stress concentration tends to occur at the contact surface between the waterstop and the concrete, leading to tearing along the anchored edge of the waterstop. A survey of the Zipingpu

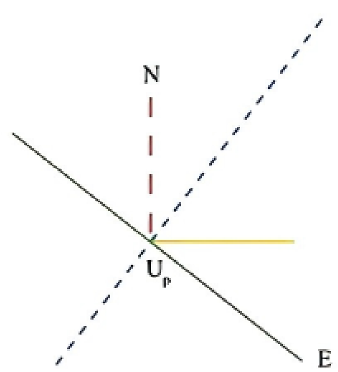
Tunnel after the Wenchuan earthquake revealed that 85% of the deformation joint failures were due to waterstop tearing, primarily because the waterstop lacked a tensile-resistant reinforcement layer and had insufficient anchorage length (only 15 cm), making it unable to transfer the tensile forces generated by large displacements.

2.2.2. Crushing failure of inter-joint filling materials

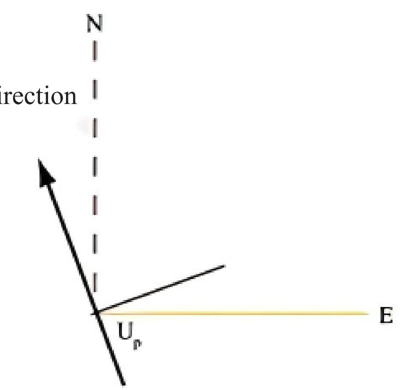
Currently, polyethylene foam boards or asphalt wood fiber boards are commonly used as filling materials for deformation joints, with a compressive strength of only 0.3–0.5 MPa. These materials are prone to irreversible plastic deformation under lateral compressive loads during strong earthquakes. In the Pingwu Tunnel after the Jiuzhaigou earthquake, the compression of the deformation joint filling material reached 60% of its original thickness, completely losing its deformation capacity and resulting in gaps of 20–30 mm wide between the joints, leading to leakage.

2.2.3. Detachment failure of anchoring structures

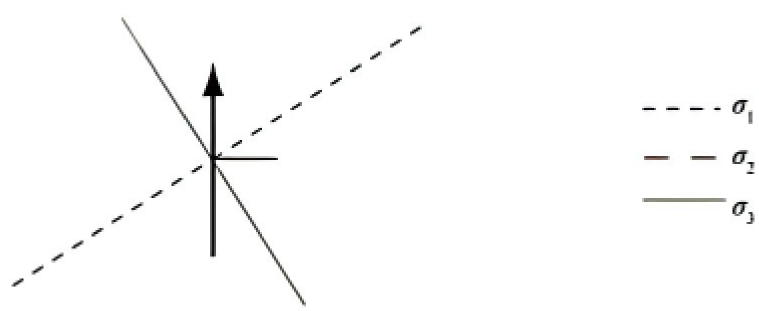
The anchoring of waterstops in traditional deformation joints relies on ordinary expansion bolts with an anchoring depth of only 8–10 cm. Under repeated seismic loading, fatigue failure tends to occur at the contact surface between the bolts and the concrete, leading to the detachment of the anchoring structure. A tunnel model test in a strong seismic zone showed that after 20 cycles of seismic wave loading, 80% of the expansion bolts became loose, with the anchoring force decreasing by more than 60% (**Figure 1**).



(a) Relationship between the principal stress tensor of ground stress and geodetic coordinates.



(b) Relationship between the longitudinal axis direction of the tunnel and geodetic coordinates.



(c) Relationship between the longitudinal axis direction of the tunnel and the principal stress tensor of ground stress.

Figure 1. Relationship between the direction of regional crustal stress field and tunnel Axis.

3. Optimized technical system for fault dislocation resistance

3.1. Material optimization: Development of highly adaptable functional materials

3.1.1. Composite reinforced waterstop strip

A composite waterstop strip is developed using a combination of natural rubber, aramid fiber, and steel wire mesh. Natural rubber serves as the matrix, with 15% nitrile rubber added to enhance aging resistance. An aramid fiber mesh with a tensile strength of ≥ 2000 MPa is embedded in the middle layer to improve tear resistance, and steel wire mesh frameworks are installed on both sides to enhance adhesion to concrete. Performance tests show that the waterstop strip achieves a tensile strength of 28 MPa and an elongation at break of 450%, can withstand longitudinal displacements of ± 150 mm without tearing, and has a service life more than 10 years longer than traditional waterstop strips.

3.1.2. Highly elastic filling material

A polyurethane elastomer filling material is developed by adjusting the ratio of isocyanate to polyol, achieving a compressive strength of 1.2–1.5 MPa and an elastic recovery rate of 95%, compared to only 30% for ordinary foam boards. Under lateral displacements of ± 80 mm, the material fully recovers its original shape after unloading and demonstrates excellent weather resistance, with no performance degradation in temperatures ranging from -30°C to 80°C, making it suitable for extreme climatic conditions in strong earthquake zones.

3.2. Structural optimization: Innovation in multi-layer protection and limit structures

3.2.1. Mortise-and-tenon limit structure for fault dislocation resistance

A mortise-and-tenon limit structure is innovated using a "tenon + groove" design. At the ends of tunnel linings on both sides of deformation joints, tenons and grooves are set with widths of 30 cm and heights of 20 cm, respectively. Stainless steel slide rails are embedded inside the tenons, and the grooves are filled with composite elastic materials. This structure restricts excessive displacements through the interlocking of tenons and grooves, providing a longitudinal limiting capacity of ± 150 mm and a lateral limiting capacity of ± 80 mm. The slide rail design also reduces friction during displacement, preventing excessive stretching of the waterstop strip.

3.2.2. Multi-layer waterstop protection system

A four-layer waterstop system is constructed using "centrally-embedded waterstop + back-adhered waterstop + water-swellable waterstop strip + sealant." The centrally-embedded waterstop is of a composite reinforced type, the back-adhered waterstop includes a butyl rubber adhesive layer with adhesive strength ≥ 1.5 MPa, and a water-swellable waterstop strip with a swelling ratio ≥ 300% is installed on the inner side of the joint. The surface layer is sealed with polysulfide sealant. This system provides three-dimensional protection, and even if one waterstop layer fails, the remaining layers block leakage paths, reducing leakage by over 90% compared to traditional constructions.

3.2.3. Reinforced anchoring structure

A combined anchoring method using "ribbed steel bars + chemical anchor bolts" is adopted. The anchoring edges on both sides of the waterstop are widened to 25 cm, with φ12 ribbed steel bars embedded at 20 cm spacing. M12 chemical anchor bolts, with an anchoring depth of 15 cm, replace traditional expansion bolts, and the anchor bolts are welded to the ribbed steel bars to form an integral structure. Pull-out tests show that the anchoring force reaches 18 kN, 2.5 times higher than that of traditional expansion bolts, and after 50 cycles of seismic wave loading, the anchoring force decreases by only 10%.

3.3. Construction optimization: Precise quality control process

3.3.1. Three-dimensional positioning and installation technology

A three-dimensional positioning method combining a total station and a laser line projector is adopted. Before lining pouring, the waterstop and tenon-mortise structures are positioned according to design coordinates, with errors controlled within ± 5 mm, and temporary fixing brackets spaced at 50 cm are installed to prevent shifting during pouring. Application in a tunnel project shows that this method achieves 100% accuracy in waterstop positioning, a significant improvement over traditional construction, which has positioning errors of ± 15 mm.

3.3.2. Layered pouring and vibration process

The lining concrete pouring process is optimized by adopting layered pouring in the deformation joint area, with each layer 30 cm thick. An immersion vibrator with a frequency of 50 Hz is used, and vibration time is controlled at 20–30 s per point to ensure tight integration between the concrete, waterstop, and tenon-and-mortise structure, preventing honeycombing and pitting. Ultrasonic testing shows that the compactness of the optimized lining concrete reaches 98%, a 15% improvement over traditional techniques.

3.3.3. Dynamic monitoring and maintenance

Displacement and stress sensors are embedded at deformation joints to monitor temperature deformation and concrete shrinkage in real time during construction. Maintenance measures, such as thermal insulation blankets and watering for curing, are adjusted based on the monitoring data. After tunnel opening, waterstop integrity is inspected regularly every six months, and leakage is checked. A closed-loop management system of “monitoring–evaluation–maintenance” is established to promptly address minor defects and prevent escalation.

4. Validation and engineering application of optimization techniques

4.1. Model test validation

A 1:5 tunnel model was constructed in the laboratory to simulate a 0.4g seismic dynamic load (fitted to the Wenchuan earthquake wave), comparing the fault-dislocation resistance of traditional and optimized structures. The results showed that the traditional structure experienced tearing of the waterstop and leakage of up to 50 L/h at a longitudinal displacement of 100 mm. In contrast, the optimized structure only exhibited slight leakage (2 L/h) at longitudinal displacements of 150 mm and transverse displacements of 80 mm, with no structural damage, demonstrating a 2.3-fold improvement in fault-dislocation resistance and meeting design requirements for strong earthquake zones (**Figure 2**).

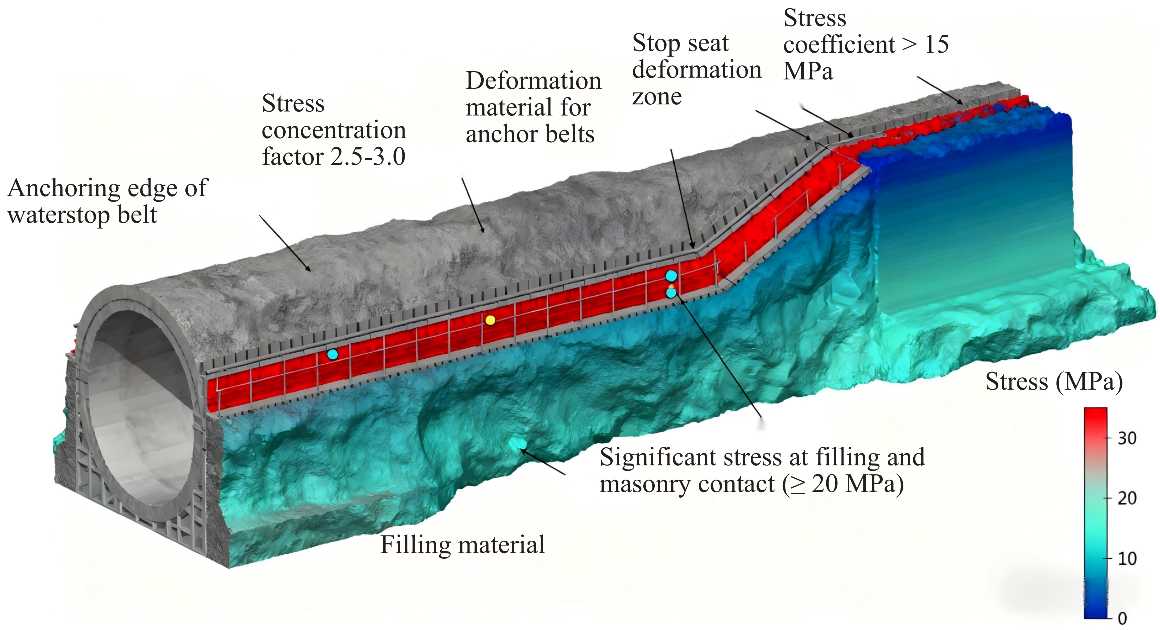


Figure 2. Finite element analysis of longitudinal deformation joints in tunnels in strong earthquake zones.

4.2. Engineering application case

4.2.1. A tunnel on the Sichuan-Tibet railway

This tunnel is located in an area with a peak ground acceleration of 0.3 g and employs the optimized fault-dislocation-resistant structure for its deformation joints. During the construction process, three-dimensional positioning and dynamic monitoring were employed to ensure the installation accuracy of the structural components. One year of monitoring after the tunnel was opened to traffic revealed that the maximum displacement of the deformation joints was 35 mm, with no leakage or structural damage, and a 100% intact rate of the waterstops, verifying the reliability of the optimized technology.

4.2.2.. A highway tunnel in Yunnan

This tunnel traverses an active fault. During the initial construction phase, the traditional deformation joints cracked due to the weak shear resistance of the rubber waterstops, influenced by the fault's micro-movements. This led to rainwater infiltration, resulting in water accumulation at the tunnel bottom and dampness on the side walls, seriously threatening the safe operation of electromechanical equipment. Subsequently, an emergency repair using optimized structures was implemented: the composite reinforced waterstops containing multi-layer fiber skeletons were replaced, enhancing tear resistance by 40%; tenon-and-mortise type limiting structures were added to restrict lateral displacement through interlocking concave and convex parts; and polyurethane elastomer material was filled to form a highly elastic sealing layer upon curing, adapting to joint deformations. After the repair, coinciding with the typhoon season, the leakage problem was completely resolved during continuous heavy rainfall. Subsequent 18-month earthquake monitoring indicated that the maximum displacement of the structure was only 3 mm, effectively accommodating minor fault displacements and demonstrating good structural stability.

5. Conclusion

The fault-dislocation resistance performance of longitudinal deformation joints in tunnels in strong earthquake zones is crucial for determining tunnel seismic safety. This paper proposes a three-dimensional optimization technology system encompassing “materials-structure-construction” by analyzing the failure mechanisms of deformation joints. The core innovations lie in the development of composite reinforced waterstops and polyurethane filling materials, addressing the issues of “easy tearing and crushing” in traditional materials; the innovative tenon-and-mortise type limiting structures and multi-layer waterstop systems achieving the dual goals of “large displacement adaptation and comprehensive leakage prevention”; and the precise construction process ensuring the effective performance of the structures. Model tests and engineering applications demonstrate that the optimized technology can significantly enhance the fault-dislocation resistance and leakage prevention performance of deformation joints, adapting to the load characteristics of “large displacements and high stresses” in strong earthquake zones. Future efforts should focus on long-term performance monitoring, optimizing design parameters based on more strong earthquake cases, and promoting technological standardization to provide replicable and scalable technical solutions for tunnel projects in strong earthquake zones, thereby enhancing the seismic resilience of vital transportation infrastructure.

Disclosure statement

The authors declare no conflict of interest.

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